

Analysis, Simulation and Construction of a simple Theremin

Author: Maria Armengol i Díaz

Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Ana Maria Vila i Arbones

Abstract: In this project we study two circuits that allow us to create a simple Theremin, one of them based on analog components and the other one on digital devices. First, we design the circuits and study them analytically, checking that in theory both are valid for our purpose. Then, we simulate them using *LTSpice* and we observe their behavior. Finally, we try to built them in order to create our own Theremin but we are only successful implementing the analog one.

I. INTRODUCTION

Lev Sergeevich Termen (1896-1993) was a Russian physicist and musician. While he was working at Ioffe Physical Technical Institute on high-frequency measurement methods he discovered that the movement of objects nearby a circuit affected the capacitance of electronic devices and caused the variation of the resonant frequency. He used that effect to create a musical instrument that is played without any physical contact between it and the interpreter. Its original name was aetherphone, but it became popular with the name of its creator: Theremin [1].

The Theremin consists of two antennas mounted horizontally and vertically respectively. The pitch is controlled by the distance between the right hand of the musician and the vertical antenna, being higher with the proximity. The distance between the left hand and the horizontal antenna determines the volume: the musician can lower the volume by approaching his or her hand.

Throughout history, different circuits have been designed to implement this instrument. The original design proposed by Lev Termen was based on vacuum valves. Later on, Robert Moog marketed a Theremin based on transistors. Today we can find several designs proposed by professionals from the area as well as for amateur builders. Regardless of the electronics behind the circuit all the designs share the same operating principle - based on the oscillation of a resonant circuit and the principle of heterodynamics - to control the pitch.

In this article we will study analytically two pitch circuits, an analog and a digital one, which could be used to implement a very basic Theremin: from a variation of few picofarads of the capacity of the antenna they achieve an oscillation in audio frequency. This theoretical study will be supported by computer simulations using *LTSpice* in order to verify our calculations. Finally we will try to implement them to see how changes our previous study by working with real devices.

II. CAPACITANCE OF THE ANTENNA

Before starting the design of the Theremin circuit we must study the antenna capacitance and the influence of

the player. The antenna acts as a plate of a capacitor, creating cylindrical lines of charge in space. Without the presence of a human body, the capacitance C_{AG} between the antenna and the ground depends on the electrical, geometrical and location characteristics of the antenna. The hand of the musician acts as a ground plate at a variable distance of the antenna, adding a new capacitance ΔC_A in parallel (Fig.1) which increases when the performer approach his or her hand [2].

We will use a radio antenna, around 48cm high, to build our Theremin. We experimentally measure its capacitance using a *Capacitance Meter model 72B* available in our laboratory. Due to the initial offset we can not be able to measure the fixed C_{AG} . We can only measure the variable capacitance ΔC_A being 0pF when the musician is far away from the antenna and around 5pF when he or she almost touches it. As a result of both contributions the antenna capacitance is given by $C_A = C_{AG} + \Delta C_A$.

Due to the impossibility of measuring C_{AG} we will use the value of 7pF given in [3] to run our simulations.

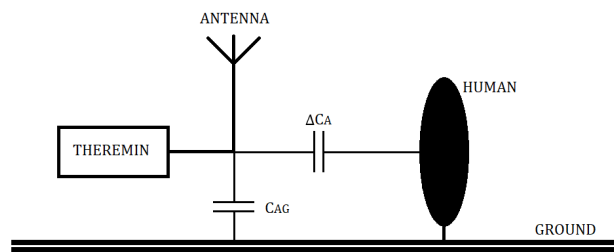


FIG. 1: Circuit diagram of capacity antenna model

III. ANALOG THEREMIN DESIGN

To design the Analog Theremin we have based on traditional designs in which two oscillators and a multiplicative mixer are used. We use a Wien Bridge as a oscillator, allowing us to study in depth a circuit presented in *Electronica Aplicada* subject of the degree of Physics. The mixer used is the diode double balanced mixer which allows us to work at the desired frequencies. The basic concept is shown schematically in Fig.2

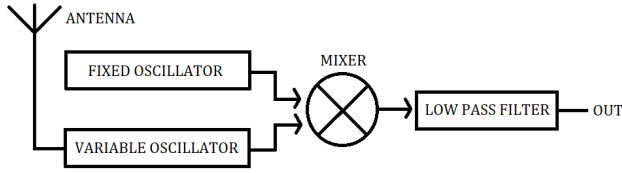


FIG. 2: Block diagram for Analog Theremin

A. Theoretical analysis

The fixed oscillator is a traditional Wien Bridge. According to [4] the frequency of oscillation is calculated equalling to zero the imaginary part of the feedback factor, $\beta = \frac{V_+}{V_{out}}$, being

$$f_{fix} = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

$$Re[\beta] = \frac{R_1}{R_1(1 + \frac{C_1}{C_2}) + R_2} \quad (1)$$

To build a variable oscillator from a Wien Bridge, we locate the antenna in parallel with R_3 and C_3 as we see in Fig.3. Therefore, we must add a new variable capacity C_A in (1), obtaining this new expression:

$$f_{var} = \frac{1}{2\pi\sqrt{R_3 R_4 C_4 (C_3 + C_A)}}$$

$$Re[\beta] = \frac{R_3}{R_3(1 + \frac{C_3 + C_A}{C_4}) + R_4} \quad (2)$$

As we see in (2) the frequency decreases with C_A . Increasing the value of this variable capacity - by approaching the hand - f_{var} is more different from f_{fix}

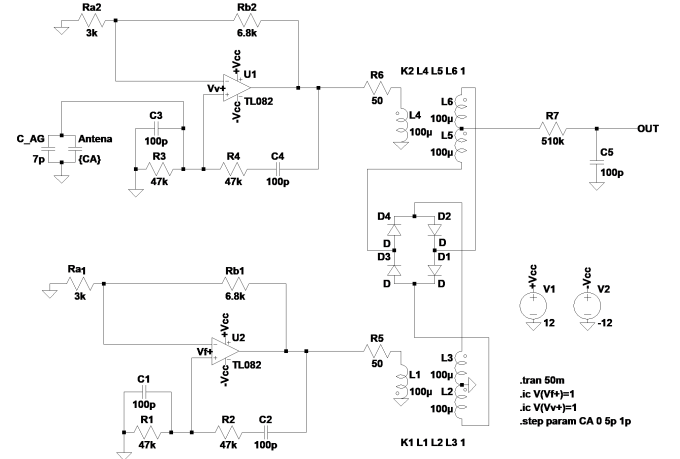
A mixer is a device that creates new frequencies by combining two input frequencies, using the heterodyning technique. The double balanced mixer uses the non-linear property of the diodes to multiply two signals. The signal of the oscillators can be expressed mathematically as $A_1 \cos \omega_1 t$ and $A_2 \cos \omega_2 t$. The multiplicative mixer provides an output given by

$$V_{MIXER} = \frac{A_1 A_2}{2} [\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t] \quad (3)$$

where we have used a standard trigonometric identity to obtain that. Thus the output signal has two frequency components. By using a low pass filter, with a cutoff frequency $f_c = \frac{1}{2\pi RC}$, we attenuated the sum frequency leaving only the beat frequency as an output of the Theremin. By choosing right values of R and C this output can be an audible signal that varies with the movement of the hand. By approaching the hand ΔC_A increases therefore the difference between f_{var} and f_{fix} also increases consequently the sound is higher.

B. Simulation

We used the OpAmp *TL082* polarized at $V_{cc} = \pm 12V$ in order to work with a real device available in the laboratory. The selected values of resistance, capacitance and inductance of the components are available in the market.

FIG. 3: Complete Analog Theremin circuit simulation using *LTSpice*

We choose values of $C_{1,2,3,4}$ of the order of picofarads, as we can see in Fig.3, so that a minor change of C_A will vary the output some hundreds of Hz. We must note that the closed-loop gain must be $A\beta \geq 1$ for all values of C_A , otherwise Barkhausen conditions will be broken and the oscillation will be attenuated to zero. Only in the case of equality the output has a sinus shape, in other cases it is saturated near the V_{cc} voltage.

As shown in Table I, simulated values of the resonant frequency are lower than the ones given by (1) and (2), with a relative error of about 13%. By changing the values of R and C we see that we only obtain the exactly theoretical solution by simulating the ideal Wien Bridge, with $R_1 = R_2$, $C_1 = C_2$ and $R_b = 2R_a$, and with values of capacitance around few nanofarads. Despite this, the frequency varies with ΔC_A as expected and the beat frequency $|f_{fix} - f_{var}|$ is still in the audio range so we can continue working with this non-ideal circuit.

The mixer's output have the contributions of the sum and the difference frequency as expected. To filter the signal we choose values of R_7 and C_5 that cutoff frequencies above 3120Hz to attenuate the sum frequencies.

The Output is a sinus wave with ripple - because the attenuation of the sum frequency is not perfect - and this frequency matches perfectly to the difference between simulation values of f_{fix} and f_{var} , confirming the ideal operation of the simulated mixer.

Analog Theremin

ΔC_A (pF)	Analytic $f_{fix} = 33.86kHz$		Simulation $f_{fix} = 29.08 \pm 0.05kHz$		
	f_{var} (kHz)	$ f_{fix} - f_{var} $ (Hz)	$f_{var}(kHz)$ ± 0.02	$ f_{fix} - f_{var} $ (Hz) ± 40	$f_{out}(Hz)$ ± 1.5
0	32.74	1126.39	28.32	760	763.3
1	32.58	1278.30	28.21	870	871.3
2	32.43	1428.11	28.12	960	979.3
3	32.29	1575.88	27.99	1090	1087.5
4	32.14	1721.65	27.90	1200	1195.1
5	32.00	1865.46	27.78	1300	1302.3

TABLE I: Analytical and simulation values of frequency of the oscillators signal and the Theremin output of the Analog Theremin

IV. DIGITAL THEREMIN DESIGN

We design a Digital Theremin using a simplification of the circuit proposed in [3], which uses logic gates as fundamental components. The general idea is the same as the analog circuit: to obtain an audio-frequency signal from the frequency difference between two oscillators. The basic concept is shown schematically in Fig.4.

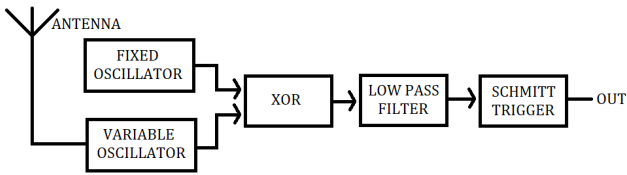


FIG. 4: Block diagram for Digital Theremin

A. Theoretical analysis

A Schmitt Trigger is a comparator with hysteresis. The gate switches at different points for positive-going and negative-going signal. The threshold voltages are V_{T+} and V_{T-} and the power supply V_{dd} is referenced to V_{ss} (usually ground). We can use it to built an oscillator as shown in Fig.5. First, V_{in} is lower than V_{T+} so V_{out} goes high (V_{dd}) and starts charging $C_{1,2}$ through $R_{1,2}$. When V_{in} crosses the threshold voltage V_{T+} , V_{out} goes low (V_{ss}) and discharging of $C_{1,2}$ through $R_{1,2}$ begins. When V_{in} crosses the negative threshold voltage V_{T-} , V_{out} goes high, hence the process starts again creating an oscillating output which frequency is given by the following equation

$$f = \frac{1}{RC \ln \frac{V_{T+}(V_{cc}-V_{T-})}{V_{T-}(V_{cc}-V_{T+})}} \quad (4)$$

In the variable oscillator we have the contribution of the capacitance of the antenna, located in parallel with C_2 , being $C = C_2 + C_A$ variable and inversely proportional to f_{var} .

The output of the two oscillators is the input of a XOR gate, giving a signal whose duty cycle varies at the difference of the input frequencies. By integrating this signal through a low-pass filter we achieve a pseudo-triangular signal with the beat frequency. Through the well-known Schmitt Trigger gate, we convert this signal into a square wave to eliminate the noise. If we have correctly designed the circuit this signal will be audible and the sound will be higher with the proximity of the hand, similarly to the analog design.

B. Simulation

We polarize all the components of the circuit between $V_{ss} = 0V(\text{ground})$ and $V_{dd} = 5V$.

We used simulated 4093B, a two-input NAND gate with $V_{T+} = 2.9V$ and $V_{T-} = 2.1V$, as a Schmitt Trigger. As in the Analog Theremin, we use values of $C_{1,2}$ of the order of picofarads, obtaining a 5V square signal that varies with C_A according to (4). In Table II are shown the values of the frequency depending on ΔC_A , which mach with the theoretical ones with only 3% of discrepancy.

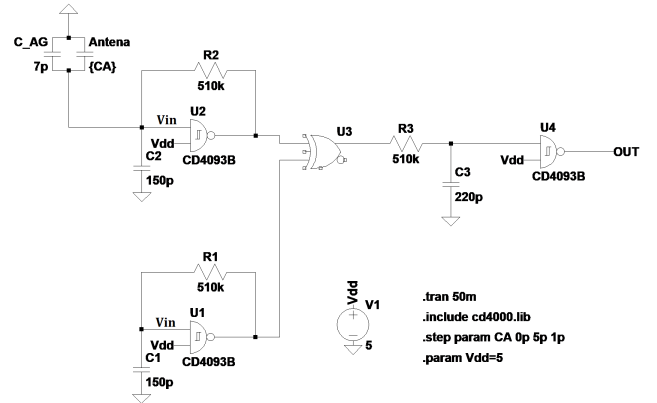


FIG. 5: Complete Digital Theremin circuit simulation using LTSpice

The XOR must have a quick response time to follow the small variations between f_{fix} and f_{var} . We simulate a XOR gate with a response time of 20ns that allows us to obtain the desired signal. Since the difference between the oscillators is at most 1500Hz, we choose the appropriate R_3 and C_3 to allow pass frequencies of this order and attenuate higher ones. The signal obtained is a sinusoidal wave with ripple. We must ensure that its amplitude is large enough to exceed the V_{T+} and V_{T-} limits of the Schmitt Trigger below. Can be seen in Table II how the final output is in agreement with $|f_{fix} - f_{var}|$ besides it is audible and increases with ΔC_A .

Digital Theremin

ΔC_A (pF)	Analytic		Simulation		
	$f_{fix} = 20.25kHz$		$f_{fix} = 19.73 \pm 0.02kHz$		
	f_{var} (kHz)	$ f_{fix} - f_{fix} $ (Hz)	$f_{var}(kHz)$ ± 0.02	$ f_{fix} - f_{var} $ (Hz) ± 40	$f_{out}(Hz)$ ± 1.5
0	19.35	902.84	18.88	850	860
1	19.22	1025.28	18.76	970	977
2	19.10	1146.19	18.64	1090	1092
3	18.98	1265.58	18.53	1200	1206
4	18.86	1383.50	18.42	1310	1317
5	18.75	1499.95	18.31	1420	1430

TABLE II: Analytical and simulation values of frequency of the oscillators signal and the Theremin output of the Digital Theremin

V. BUILDING A THEREMIN

During the experimental assembly of the circuits many of the technical problems of this project have emerged. It is also when we have seen the limitations of the different components used and we have observed the actual operation of these.

We have used the *Power Supply FAC-662B* to polarize our circuits, and by means of a *TBS 1052B-EDU Digital Oscilloscope* we have visualized the output signal of each stage.

A. Analog Theremin

We had technical complications building this circuit, which we will explain below. First we mount the fixed oscillator successfully obtaining an output of $46.7 \pm 0.1kHz$ - with a relative error of 27% respect the analytic solution that we could attribute to experimental and measurement uncertainties-. It is at the time of mounting the variable oscillator when we have a problem. Without connecting the antenna, the circuit oscillates like the fixed one at $46.7 \pm 0.1kHz$ but when we connect the antenna we see that the oscillation frequency does not change, and by approaching the hand it still does not decreases as we expected. The circuit is not sensitive to the presence of the antenna. We attribute this fact to that the capacitance variation is too small to change significantly the oscillation frequency of the *TL082*.

B. Digital Theremin

We have been able to successfully build a very simple Theremin from the digital circuit previously studied.

We start with the construction of the oscillators. We use a Schmitt Trigger *CD4093B* and we verify experimentally that $V_{T+} = 2.9V$ and $V_{T-} = 2.1V$. We use the

values of $C_{1,2}$ and $R_{1,2}$ indicated in Fig.4 - initially we try to use lower values but thanks to the experimental realisation, and according to the Datasheet, we have found that for a correct operation of the oscillating circuit it must be $50k\Omega \leq R \leq 1M\Omega$ and $100pF \leq C \leq 1\mu F$ -. Before connecting the antenna in the variable circuit we see that the frequency of the output of the two circuits is slightly different, being $23.0 \pm 0.1kHz$ for the fixed one and $22.5 \pm 0.1kHz$ for the variable, when they should be the same. It is because of working with real components and not with simulated ones. Both values are sufficiently similar (10% of relative error) to the analytical and simulated ones in Table II. Connecting the antenna to the variable circuit causes an immediate decrease of the frequency to $21.4 \pm 0.1kHz$ which, as we have said previously, we attributes to the capacity C_{AG} between the antenna and the ground. Approaching the hand to the antenna we get a signal of $21.0 \pm 0.1kHz$. Those results are accord to (4), being $C = C_2 + C_{AG} + \Delta C_A$ where $C_{AG} = 8 \pm 1pF$ - instead of $7pF$ as we assumed at the beginning of the work - is fixed and $\Delta C_A = 0 - 4 \pm 1pF$ varies with the movement of the hand.

We introduce the two signals into the XOR *74ls86* obtaining a periodic signal that, filtered, gives us a signal whose frequency is the difference between them, about $1.6 - 2.1 \pm 0.1kHz$. We use a third Schmitt Trigger to eliminate the noise and achieve a square wave of 5V of amplitude. This output is in the audio-frequency so we can hear it using a *0.25W ROHS speaker* properly connected.

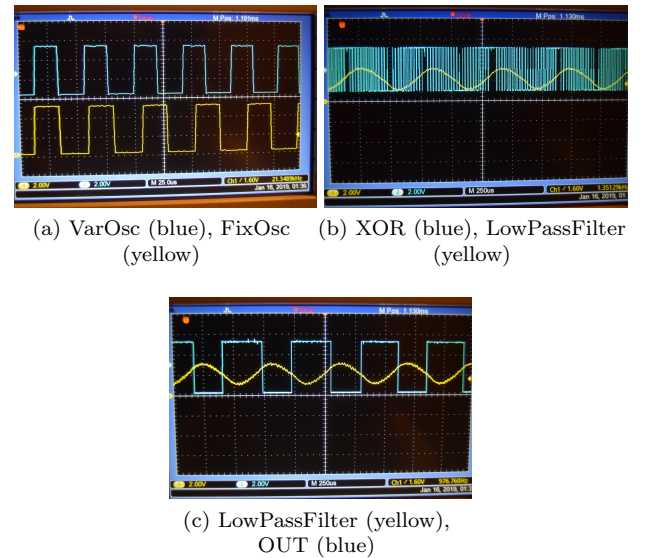


FIG. 6: Signal of each block visualized on the oscilloscope

By using a *Chromatic tuner CA-30*, we verify that the range of notes on the music scale of our Theremin goes from a low G#6 ($1661.22Hz$) to a C7 ($2093.00Hz$).

VI. CONCLUSIONS

- We have been able to perform a theoretical study of the operation of two different circuits, understanding the physics behind each of their stages and the equations that govern them.
- Through the simulations with *LTSpice* we have been able to visualize the signal and its dependence with the values of the different components, as well as see how the operation moved away from the ideal analysis.
- Building the experimental setup we have known the limitations of our circuits. We have discarded the analog circuit when we see that it did not work as we expected, attributing this fact to problems of sensibility of the devices. For future work, these experimental problems could be studied in depth in order to solve them and built successfully an Analogic Theremin based on Wien Bridges. In contrast, we have been able to develop a very basic Theremin from the digital design studied. This Theremin is purely an academic work, since it allows us to study each of the stages of the circuit, but it can not be considered a musical instrument. Its sound is un-

stable and imprecise, and only supplies a half of an octave therefore is very limited to play music. In addition, the antenna only detects the presence of the hand at a very short distance, so we must work practically by touching the antenna to change the note, which makes the performance very difficult.

- An obvious difference between the two circuits is the form of the output signal, being sinusoidal in the analog one and square in the digital one. This entails a different loudness that we have not been able to hear since we have not been able to build the first circuit.

Acknowledgments

I would like to thank my advisor Ana Maria Vila for the original idea of this work and her guidance during the project. I would also like to thank the department of Enginyeria Electronica for let me access in their laboratory and use their equipment throughout the circuit construction phases. Finally I want to thank my family and friends, for their encouragement during all the years of my education.

-
- [1] P. V. Nikitin, "Leon Theremin (Lev Termen)", *IEEE Antennas and Propagation Magazine* **54** (2012) 252-257.
 - [2] W. Buller and W. Brian, "Measurement and Modeling Mutual Capacitance of Electrical Wiring and Humans", *IEEE Transactions on Instrumentation and Measurement* **55** (2006) 1519-1522.
 - [3] K. D. Skeldon, L. M. Reid, V. McInally, B. Dougan and C. Fulton, "Physics of the Theremin", *American Journal of Physics* **66** (1998) 945-955
 - [4] J. M. Fiore, *Amplificadores operacionales y circuitos integrados lineales* (Delmar Thomson Learning, Madrid, 2001)